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L. I. DORMAN, A. I. KUZ'MIN, G. V. TYANUTOVA Ye. L. FEYNBERG
and Yu. G. SHAFER.

Variations of intensity of cosmic rays and the role of meteorological factors.

A short exposition of the results of experimental and theoretical investigation of the influence of meteorological factors on the observed (at sea level) intensity of the hard component of cosmic rays is presented. It is shown that, knowing the distribution of temperature of the atmosphere above the point of observation it is possible to calculate the meteorological factor with a precision of up to 0.1 - 0.2% in the intensity of cosmic rays (in which case the remaining divergence lies within the limits of error of the data of meteorological sounding).

It turns out that (with this precision) seasonal variations of intensity of the hard component are fully conditioned by meteorological factors. Diurnal changes are, to a material degree, masked by these factors.

The study of the variations of intensity of cosmic rays is a matter of considerable interest. In the first place, some of them are conditioned by changes in the earth's atmosphere and therefore information on the character of the interaction of cosmic rays with matter and on the nature of particles in cosmic rays can be extracted from this. Secondly, having reliably excluded those variations of geophysical origin, it is possible to obtain information necessary for explaining the problem of the mechanism and place of generation of cosmic rays. Thirdly, the knowledge of the character of the connections between variations of the intensity of cosmic rays and solar activity, the state of the Earth's magnetic field and fluctuations of meteorological parameters will help the further study of these phenomena.

In 1928 MYSOVSKY [1] discovered the barometric effect, a convincing confirmation of the extra-terrestrial origin of cosmic rays. This was the first work in the U.S.S.R. on the study of the variations of intensity of

cosmic rays. In recent years a number of theoretical and experimental results have been obtained from the study of this question; the exposition of some of them comprises the basic content of the present article.

The hard component of cosmic rays has been subjected the most frequently to investigation. To the number of periodic fluctuations of its intensity belong the 11 - year (decennial) seasonal (annual), 27 - day (monthly) and diurnal fluctuations. Seasonal variations in the limits of the northern part of the U.S.S.R. reach 5%; the remainder (except the decennial) reach a weaker degree (they are measured in tenth parts of one per cent). Both for the explanation of interaction with the atmosphere and for the problem of the origin of cosmic rays, it is important, first of all, to isolate the variations of intensity of the hard component of cosmic rays connected with meteorological changes in the earth's atmosphere.

In 1937 BLACKETT /2/ pointed out the existence, together with the barometric effect, of a temperature effect for mesons, reduced, according to BLACKETT, to the statement that with warming, (e.g. in summer) the atmosphere expands, the level of generation of mesons, in this case, rises, and the decomposition of mesons increases. By this, the order of magnitude of phenomena observed at sea-level can be explained. However, in subsequent foreign experimental works /3-5/, and many other earlier ones (the number of which is numbered in tens) unsuccessful attempts, on the basis of precise measurements over many years of the variations of the intensity of the hard component of cosmic rays, were made to explain by meteorological effects the seasonal changes of intensity of cosmic rays, having obtained more precise temperature effect.

In foreign literature at ~~one~~ the present time this question is extremely complicated. It is sufficient to say that, in a survey in 1952 /6/, in for example, the article of DOLBEAR and ELLIOT, it was shown that in seasonal variations, after taking into account the decomposition of mesons, there seemed to remain an equally powerful seasonal effect of the reverse

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sign (so-called positive temperature effect). An effect of such a sign ought, indeed to be obtained if the competition between decomposition and capture of π -mesons generating μ- mesons is taken into account, but it ought to be several (up to three) times less than that calculated by these authors and also in work /4/ from observations.

However the whole conclusion that to take into account the decomposition of the meson does not remove the seasonal effect, but strengthens it, is, as we shall see, based on a misunderstanding. The following circumstance plays a considerable role in the creation of this misunderstanding.

Meterological effects are usually reduced to two : barometric (simple increase of the absorption of mesons with the growth of the mass of matter above the apparatus) and temperature (displacement of the level of generation of the mesons with change of temperature of the atmosphere). During calculation of temperature effect the question arises : which temperature of the atmosphere should be taken into account here? Between sea level and the level of generation the temperature of the atmosphere differs by 60 - 80 deg. and its change at different levels is not uniform. Thus, at sea level in summer it is warmer than in winter whilst at the level of generation in a number of places (England, North America) it is colder in summer. At sea level in Siberia it is colder than at the equator, but in the stratosphere it is warmer, etc.

In a number of works ill-conceived attempts were made during the calculation of temperature effect to construct a so-called "single" temperature coefficient out of the changes of temperature of the layer of atmosphere nearest the earth or, on the other hand, of the stratosphere part, or an average of these two temperatures or an average of the temperatures of a certain part of the atmosphere. In these circumstances mutually contradictory results were obtained.

Meanwhile the question, as was shown even in 1946, allows of a simple and general solution.

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First of all, attention should be directed to the existence, apart from barometric effect and the effect of the displacement of the level of generation of mesons, of another equally important effect: the lifetime of the meson depends on its energy. Therefore the probability of decomposition grows as the meson approaches the Earth as a result of ionisation losses. Where — at the beginning or end of the path -- the meson loses this energy, is of very material importance. In other words, the probability of reaching the Earth changes with the re-distribution of masses even at a constant height of level of generation. Hence calculation of the non-equilibrium of the atmosphere during analysis of the experiment is essential.

Calculation of the change of meteorological factors, as can be easily shown is determined in fact for the vertical flow of mesons by the following formula, in which we neglect only the spreading /RAZMAZANNOST'/ of the level of generation and the competition between decomposition and capture of π-mesons, generating μ-mesons. /1/ ;

$$\frac{\delta N_\mu}{N_\mu} = A\,\delta h_0 + B \int_{h_1}^{h_0} \frac{\delta T(h')\,dh'}{h'\left[cp_1 - a(h'-h_1)\right]T(h')} \qquad (1)$$

Here N_μ is the probability of μ mesons reaching the point of observation and δN_μ is its change; δh_0 is the change of pressure at the point of observation; h_1 is pressure at the point of generation where the impulse of the particle is p_1; a is the ionisation losses per g/cm^2 of the air; $\delta T(h')$ is the change of temperature T at the point with pressure h'; A, B are coefficients depending on the mass of the μ-meson m_μ, its lifetime at rest τ_0, temperature and density of the air at the point of observation $\rho(h_0)$,

$$A = \frac{mc^2}{\rho(h_0)\,\tau_0}\,\frac{1}{cp_1 + a(h_0 - h_1)}; \quad B = \frac{mc^2}{c\,\tau_0}\,\frac{h_0}{\rho(h_0)}$$

In formula (1) its first member gives the barometric effect, in the second is included the complicated influence of changes of temperature in a heterogeneous(?) atmosphere /not in a state of equilibrium/

In 1949-50, after averaging according to the spectrum of the mesons and according to angles, formula (1) was extended to the case of global intensity. Up to recent times this generalised formula was also utilised by

by us for theoretical forecasting of meteorological effect and it enabled us to obtain this important result ; it was shown that the seasonal variation of intensity of the hard component of cosmic rays is almost wholly explained by the influence of meteorological factors. In view of this the necessity of further precision of the formula (1) arose.

At the beginning of 1952, formula (1) was newly generalised [8] on a two-meson diagram, based on the supposition that μ - mesons appear as the result of the decomposition of π - mesons generated by the primary component in the thickness of the atmosphere, which can both decompose and be captured by nuclei. By this, the so-called positive temperature effect is calculated. The change introduced by the possibility of the capture of π -mesons is, generally speaking, not great; it is considerable only for great depths under the earth.

Confirmation of the correctness of such a hypothesis can be seen in the fact that the generation spectrum of π -mesons, obtained from comparison of the theoretical variation with height of μ -mesons with the experimental (utilizing the well-known data of GRIGOROV [9]) agrees well with POWELL'S generation spectrum [10].

On the basis of the formulae obtained, auxiliary graphs were constructed, from which, knowing the temperature cross section of the atmosphere and pressure at the point of observation, it is easily possible to calculate the change of intensity of cosmic rays δN_μ conditioned by the change of meteorological factors. According to this theoretical diagram, data of continuous registration of fluctuations of cosmic ray intensity were elaborated in order to exclude the influence of meteorological effect. Experimental data of fluctuations of global intensity of the hard component of cosmic rays were obtained by us with great precision - up to a few hundredth parts of one per cent over one hour of observation.

From these data of changes of intensity of the hard component of cosmic rays at two different points of the Soviet Union we obtained curves of the seasonal variation of the intensity of cosmic rays. The values of

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these variations of intensity of cosmic rays were measured at the same times as the radio-soundings of the atmosphere were carried out and, consequently, at the same times for which the calculation of δN_μ was carried out. Thus, simultaneously with the observation of the seasonal variation of intensity of the hard component δI with the help of the afore-mentioned diagrams of calculations and data of radio-sounding, we obtained the theoretically expected seasonal variation δN_μ conditioned by purely meteorological causes.

For point No. 1 (measurements 1951-1952) curves of seasonal variation δI and δN_μ are shown at Fig. 1, where the unbroken curve shows the theoretically expected seasonal variation of intensity δN_μ, calculated according to meteorological data and the dots show the experimental data of continuous registration δI

Fig. 1. Unbroken line - curve of seasonal variations δN_μ of intensity of the hard component of cosmic rays, conditioned by meteorological factors, calculated according to [illegible] from data of meteorological sounding of the atmosphere over point No. 1 ([illegible]). [illegible] experimental data of variations of intensity δI, measured at the same point over the same periods. Average statistical errors of measurement of intensity $\sigma(\delta I) = \pm 0.07\%$ errors in calculated values, conditioned basically by errors in measurement of meteorological data, $\sigma(\delta N_\mu) = \pm 0.08\%$

Fig. 2. Curves of seasonal variation δI according to data of measurements in [illegible] ([illegible]) and pre-calculated from meteorological data of radio-sounding of the atmosphere above the region of [illegible] of variations of intensity δN_μ. Calculation carried out according to simplified (one-[illegible]) diagram. [7]

Besides this, seasonal variations δN_μ for the [illegible] station near [illegible] ([illegible]) was obtained by utilizing this same method and compared (Fig. 2) with published details of continuous registration δI at this station over ten years; for calculations produced according to the simpler formula (1) (one-[illegible] diagram) data of radio-sounding of the atmosphere [illegible] were used. [11]

Results of measurements and calculations are presented also in the following table:

Point of Observation	Time of Obser-vation	Seasonal effect (Amplitude of annual variation)		Coefficient of correlation
		Measured %	Calculated according to meteorological data	
U.S.S.R. Point No. 1	1951-1952	2.0	2.2	0.99 ± 0.004
U.S.S.R. Point No. 2	1949-1950	5.0	4.9	0.91 ± 0.03
U.S.S.R. Point No. 2	1951-1952	3.6	3.4	0.92 ± 0.014
U.S.A. CHELTENHAM	1937-1946	1.4	1.3	0.89 ± 0.03

The residual difference $\overline{\delta I} - \overline{\delta N_\mu}$ of the order of 0.1 - 0.2% does not exceed the limits of error of measurements of the temperature of the atmosphere and measurements of δI

Thus we can confirm that with the precision indicated, the seasonal effect for the hard component of cosmic rays is fully explained by meteorological factors. However the authors of work /3/, introducing, as we have said, a correction for the decomposition of mesons, did not compensate the measured variations and obtained a residual seasonal effect of the same absolute value (1.8%) as that measured, but of the opposite sign. As can be easily shown /12/, the reason for this lies in the incorrect calculation of the influence of the decomposition of μ mesons where the temperature distribution of the atmosphere was not borne in mind. Incomplete calculation of the influence of meteorological factors in work /4/ led to the erroneous interpretation of positive temperature effect which was explained by the effect of π mesons. In fact the result obtained in /4/ is explained (see /12/), basically by the fact that the author did not take into account the effect of redistribution of masses and the effect of the spreading /RAZMAZANNOST'/ of the level of generation which play a special role, because at the point of measurement of the work /4/ the temperature in the stratosphere has a seasonal variation, the reverse of the seasonal variation at earth level.

Fig. 3. The density of the temperature coefficient $W(h')$ for μ and π ... which the

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change of temperature at a given point $\delta T(h')$ should be multiplied. Having integrated this product according to height h', we obtain a value corresponding to the second member in formula (1) for the case of observations at sea level. The utilization of only the lower curve gives the effect for the "one-meson diagram". The upper curve gives the contribution (possessing reverse sign) from the competition between capture and decomposition of π-mesons. The full effect is given by the sum of both curves:

$$\delta N_\mu = \int_0^{h_0} W(h')\ \delta T(h')\,dh'$$

Fig. 4. The daily effect of variations of intensity of the hard component of cosmic rays, obtained by averaging data of measurements (U.S.S.R. point No. 2) over 1949-1952 (white circles). The black circles show the theoretically expected changes of intensity of the meson component δN_μ conditioned by meteorological factors and calculated from the averaged data of daily meteorological sounding of the atmosphere at the hours indicated. The average error of measurements δI is equal to $\pm$ 0.02%.

Theoretical calculations show that for intensity of cosmic rays, observed at sea level, the effect of change of temperature at a great height on π mesons is 4-5 times weaker than on μ mesons; therefore the temperature effect of the atmosphere is negative. (Fig. 3).

Incorrect calculation of meteorological factors, in particular, neglect of the above-mentioned effect of re-distribution of masses, led, at one time, even the author of /5/ to the erroneous conclusion that the seasonal changes of intensity of cosmic rays are not reduced to meteorological changes and are half explained, in his terminology, "by variations of the second kind" (world variations). Our results obviously refute this conclusion.

With the same mistake are also connected the conclusions made in /13/ where it was found that a substantial part of the latitude effect of intensity of cosmic rays was reduced to a meteorological effect. Calculations made as above gave different results which definitely showed that the latitude meteorological effect of intensity of cosmic rays at sea level does not exceed 3-4%, and at a height of 10 km it is not more than 1%. /14/.

Diurnal changes of intensity of cosmic rays are of a lower order than seasonal and their study requires far more care in the determination of diurnal changes of the temperature of the atmosphere at various levels. Besides this,

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the separation of meteorological factors in the daily course of variations of cosmic rays requires round-the-clock repeated radio-soundings considerably more frequent and more precise than those undertaken up till now by meteorologists.

Precise observations carried out by us in the U.S.S.R. have enabled us to obtain a large quantity of sufficiently reliable material which clearly indicates the existence of a diurnal effect in the intensity of the hard component of cosmic radiation with an amplitude of 0.2%, with a maximum around mid-day. (Fig. 4) From Fig. 4 it can be seen that two points pre-calculated according to meteorological data for $\delta M \mu$ at mid-day and midnight are in opposite phase, corresponding to the points of the observed diurnal course of variations (as distinct from the result of work [3], the error of which is shown in [12]).

Results of observations, and calculations for point No. 2 showed that after introduction of correction for meteorological effect, the amplitude of diurnal variation I is roughly doubled (0.4%). However, errors of diurnal measurements of temperature of high layers of the atmosphere, conditioned by radiation heating of radio-sondes are still so great (at the present time) that this conclusion requires further careful testing. If this conclusion is true, then it means that the daily effect of variations I of non-meteorological origin possessing the reverse sign to the meteorological effect, actually exists and has an amplitude of about 0.3-0.4%.

In connection with the problem of the diurnal effect in changes of the fundamental interest lies in the calculation of the influence of the changes of condition of the so-called ozone layer. According to preliminary experimental data of measurements of temperature of the ozone layer, it turns out that the amplitude of diurnal fluctuations of its temperature attains considerable magnitude and is of the sign opposite to the amplitude of fluctuations of temperature of the layer of air nearest the earth.

According to theoretical calculations, the basic portion of the diurnal variations δI could be explained by redistribution of masses in the ozone layer and in conjunction with them, of the upper layers of the atmosphere, if the fluctuations of temperature of the ozone layer attained 70-100°. However, experimental data give no foundation for such propositions.

We note that certain experiments were carried out even earlier (see, for example, [3]), in which the influence of meteorological factors was automatically /excluded.

excluded. Measurements of intensity of cosmic rays were carried out at medium latitudes by two telescopes, one of which was directed parallel to the earth's axis, and the other perpendicular to it. Thus, in spite of the daily rotation of the earth, intensity of radiation coming roughly from one point of the sky was measured the whole of the time by one telescope, whilst the other telescope collected over the 24 hours, radiation coming from various points of the sky. Therefore the difference of readings given by the two telescopes, from which the meteorological effect drops out, should give the simple diurnal effect of extra-terrestrial origin. Measurements carried out in /3/ indicate the existence of such diurnal effect in the intensity of cosmic rays with an amplitude at least equal to around 0.1%.

To the examined group of questions belong the non-periodical changes connected with the passage of meteorological fronts which are the boundaries of separation of various air masses. The considerable experimental material collected at the present time at point No. 2 has enabled us to confirm reliably the existence of a so-called " front effect " (noted in work /15/) in δI of the order of 0.3 ÷ 0.8%. Results are in any case in qualitative and even semi-quantitative agreement with the theoretical notions set out above.

More precise theoretical quantitative analysis is made difficult as a result of the absence of sufficiently precise experimental data on the temperature of the atmosphere and on measurement of the intensity of the hard component of cosmic rays over small intervals of time.

To the number of non-periodical variations, possibly of a meteorological character belong also small increases (of the order of 0.2 ÷ 0.3%) of the intensity of the hard component of cosmic rays during the time of discontinuation of radio-communication and of small solar flares. These phenomena are accompanied by an increased flow of ultra-violet radiation which can lead to the lowering of the temperature of the ozone layer by several tens of degrees. Such a lowering of temperature causes, in its turn, a certain increase of intensity of cosmic rays. This conclusion, in particular, explains the fact that effects of small solar flares in cosmic rays are observed only on the day side of the earth.

However, the conclusion on the meteorological origin of effects of small solar flares requires additional testing since changes of temperature of the ozone

ozone layer during the time of discontinuation of radio-communication and small solar flares have not been established with sufficient reliability.

The results set out show that meteorological factors play a substantial part in the variations of intensity of the hard component of cosmic rays. At the present time we are able to calculate with considerable precision the meteorological part of variations according to data of the meteorological sounding of the atmosphere. Results of investigations lead us to the conclusion that seasonal variations are reduced almost wholly to the meteorological; diurnal variations are substantially masked by them, and, in actual fact are twice as great as those observed.

In conclusion we note that in this work we constantly made use of the advice of S. N. VERNOV and N. L. GRIGOROV. Besides this, in the carrying out of measurements, the following took part - G. A. ANDREYEVA, L. N. BELYAYEV, N. V. ZEROVA, D. D. KRASIL'NIKOV, K. I. POL'SKAYA, G. V. SKRIPIN, V. D. SOKOLOV, N. V. TYUTIKOV and A. I. YUKHMANKOVA. The authors express deep gratitude to these colleagues for the extensive help given them in this complex work.

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29th October, 1953.

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мы получили теоретически ожидаемый сезонный ход δN_μ, обусловленный чисто метеорологическими причинами.

Для пункта № 1 (измерения 1951—1952 гг.) кривые сезонного хода δI и δN_μ представлены на рис. 1, где сплошной кривой показан теоретически ожидаемый сезонный ход интенсивности δN_μ, рассчитанный по метеорологическим данным, а точками — экспериментальные данные непрерывной регистрации δI.

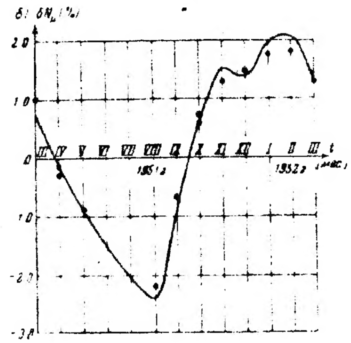

Рис. 1

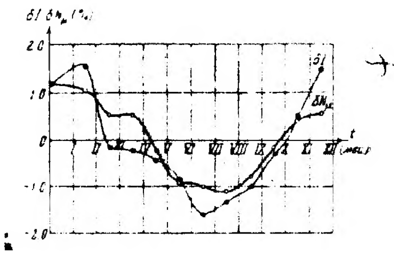

Рис. 2

Рис. 1. Сплошная линия — кривая сезонного хода вариаций δN_μ интенсивности жесткой компоненты космических лучей, обусловленного метеорологическими факторами, вычисленная по [9] из данных метеорологического зондирования атмосферы над пунктом № 1 (СССР), ● — экспериментальные данные вариаций интенсивности δI, измеренные в том же пункте за те же сроки. Средние статистические ошибки измерения интенсивности $\sigma(\delta I) = \pm 0{,}07\%$; ошибки в вычисленных значениях, обусловленные в основном ошибками в измерении метеорологических данных, $\sigma(\delta N_\mu) = \pm 0{,}08\%$

Рис. 2. Кривые сезонного хода δI по данным измерений в Челтенхеме (США) и предвычисленных из метеорологических данных радиозондирования атмосферы над районом Челтенхема вариаций интенсивности δN_μ. Расчет производился по упрощенной (одномезонной) схеме [7]

Кроме того, был получен, с использованием этой же методики, сезонный ход δN_μ для станции Челтенхем вблизи Вашингтона (США) и сравнен (рис. 2) с опубликованными данными непрерывной регистрации δI на этой станции за 10 лет, причем для расчетов, производившихся по более грубой формуле (1) (одномезонная схема), были использованы данные радиозондирования атмосферы над Вашингтоном [11].

Результаты измерений и расчетов представлены также в следующей таблице:

Пункт наблюдения	Время наблюдения	Сезонный эффект (амплитуда годового хода): Измерено, %	Сезонный эффект (амплитуда годового хода): Вычислено по метеорол. данным, %	Коэффициент корреляции
СССР, пункт № 1	1951—1952	2,0	2,2	0,99±0,004
СССР, пункт № 2	1949—1950	3,0	4,9	0,91±0,03
СССР, пункт № 2	1951—1952	3,6	3,4	0,92±0,014
США, г. Челтенхем	1937—1946	1,4	1,3	0,89±0,03

Остающаяся разница $\delta I - \delta N_\mu$ порядка 0,1—0,2% не выходит за пределы погрешностей измерений температуры атмосферы и измерений δI.

Таким образом мы можем утверждать, что с указанной точностью сезонный эффект для жесткой компоненты космических лучей полностью объясняется метеорологическими факторами. Однако авторы ра-

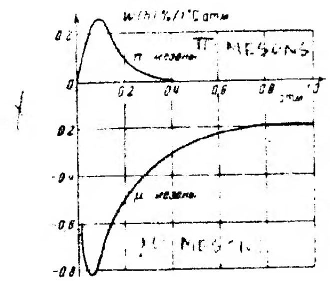

Рис. 3

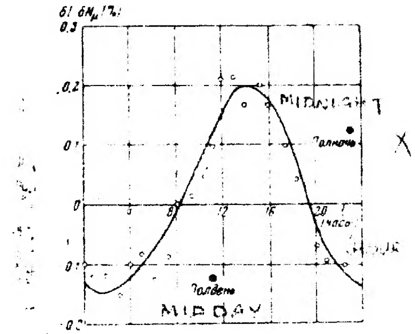

Рис. 4

Рис. 3. Плотность температурного коэффициента $W(h')$ для μ- и π-мезонов. Кривые указывают для каждого уровня коэффициент, на который следует умножить изменение температуры в данной точке $\delta T(h')$. Проинтегрировав это произведение по высоте h', получаем величину, соответствующую второму члену в формуле (1) для случая наблюдений на уровне моря. Использование одной только нижней кривой дает эффект для «одномезонной схемы». Верхняя кривая дает вклад (имеющий обратный знак) от конкуренции между захватом и распадом π-мезонов. Полный эффект дается суммой обеих кривых:

$$\delta N_\mu = \int_0^{h_0} W(h')\,\delta T(h')\,dh'$$

Рис. 4. Суточный эффект вариаций интенсивности жесткой компоненты космических лучей, полученный усреднением данных измерений (СССР, пункт № 2) за 1949—1952 гг. (светлые кружки). Черными кружками обозначены теоретически ожидаемые изменения интенсивности мезонной компоненты δN_μ, обусловленные метеорологическими факторами, вычисленные из усредненных данных ежесуточного метеорологического зондирования атмосферы в указанные часы. Средняя ошибка измерений δI равна $\pm 0{,}02\%$

боты [3], вводя, как мы говорили, поправку на распад мезонов, не скомпенсировали измеренные вариации, а получили остаточный сезонный эффект такой же абсолютной величины (1,8%), как измеренный, но обратного знака. Как легко показать [12], причина этого лежит в неправильном учете влияния распада μ-мезонов, при котором не принимается во внимание температурное распределение атмосферы. Неполный учет влияния метеорологических факторов в работе [4] привел к ошибочной интерпретации положительного температурного эффекта, который был объяснен эффектом π-мезонов. На деле полученный в [1] результат объясняется (см. [12]) в основном тем, что автор не учитывал эффекта перераспределения масс и эффекта размазанности уровня генерации, играющих особую роль из-за того, что в пункте измерений работы [1] температура в стратосфере имеет сезонный ход, обратный сезонному ходу наземной температуры.

Теоретические расчеты показывают, что для интенсивности космических лучей, наблюдаемой на уровне моря, эффект изменения температуры на большой высоте на π-мезонах сказывается в 4—5 раз слабее,

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